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Origins of Late- Pleistocene Coastal Dune Sheets, Magdalena and Guerrero Negro, from Continental Shelf Low-stand Supply (70-20 ka), under Conditions of Southeast Littoral- and Eolian-Sand Transport, in Baja California Sur, Mexico

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Origins of late- Pleistocene coastal dune sheets, Magdalena and Guerrero Negro, from continental shelf low-stand supply (70–20 ka), under conditions of southeast littoral- and eolian-sand transport, in Baja California Sur, Mexico

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ABSTRACT

Shallow morpho-stratigraphic sections (n = 11) in each of two large coastal dune sheets including the Magdalena (7000 km^2) and Guerrero Negro (8000 km^2) dune sheets, from the Pacific Ocean side of Baja California Sur, Mexico, have been analyzed for dune deposit age. The shallow morpho-stratigraphic sections (~2–10 m depth) include 11 new TL and 14C ages, and paleosol chronosequences, that differentiate cemented late Pleistocene dune deposits (20.7 ± 2.1 to 99.8 ± 9.4 ka) from uncemented Holocene dune deposits (0.7 ± 0.05 to at least 3.2 ± 0.3 ka). Large linear dune ridges (5–10 m in height) in the dune sheet interiors trend southeast and are generally of late Pleistocene age (~70–20 ka). The late Pleistocene dune deposits reflect eolian transport of marine sand across the emerged continental shelf (30–50 km southeast distance) from low-stand paleo-shorelines (−100 ± 25 m elevation), which were locally oriented nearly orthogonal to modeled deep-water wave directions (~300° TN). During the Holocene marine transgression, onshore and alongshore wave transport delivered remobilized shelf-sand deposits to the nearshore areas of the large dune sheets, building extensive barrier islands and sand spits. Submerged back-barrier lagoons generally precluded marine sand supply to dune sheet interiors in middle to late Holocene time, though exceptions occur along some ocean and lagoon shorelines. Reactivation of the late Pleistocene dune deposits in the dune sheet interiors lead to generally thin (1–3 m thickness), but widespread, covers of Holocene dune deposits (0.41 ± 0.05 to 10.5 ± 1.6 ka). Mechanical drilling will be required to penetrate indurated subsoil caliche layers to reach basal Pleistocene dune deposits.

1. Introduction

Large coastal dune sheets in the central west coast of North America are widely dispersed (Fig. 1), reflecting abundant, but highly localized, coastal sand supply from 1) major rivers, 2) alongshore littoral transport, and/or 3) long-term accumulations of sand in adjacent continental shelf areas (Cooper, 1958, 1967; Dupré and Tinsley, 1980; Blount and Lancaster, 1990; Murillo De Nava et al., 1999; Knott and Eley, 2006; Peterson et al., 2007, 2009, 2015). Two of the largest coastal dune sheets in North America, the Magdalena and Guerrero Negro dune sheets in Baja California Sur, Mexico, (Inman et al., 1966; Murillo De Nava et al., 1999; Kasper-Zubillaga and Zolezzi-Ruiz, 2007) are not associated with major rivers. The present Pacific Ocean shorelines of the Baja California Peninsula are generally characterized by narrow beaches, rocky headlands, and pocket-beach embayments. Such segmented littoral systems were probably too disconnected to have supplied the substantial abundances of littoral sand that produced the Magdalena and Guerrero Negro dune sheets. However, paleo-shoreline

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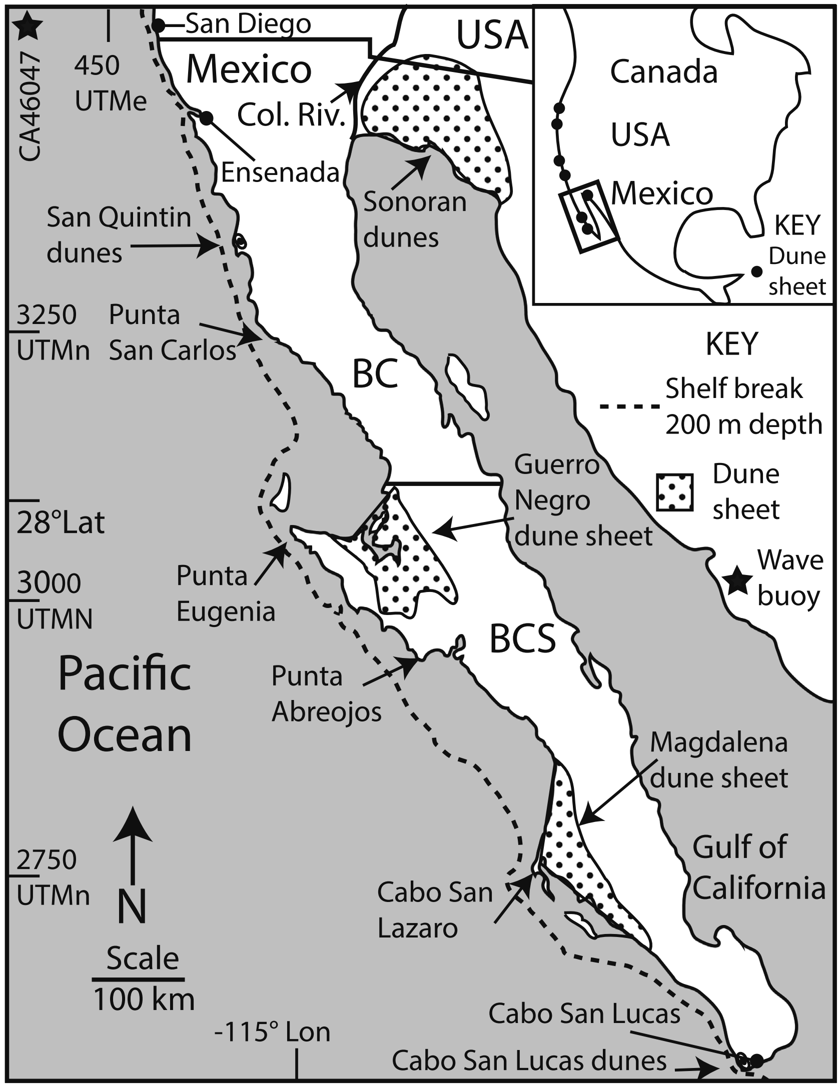

Fig. 1. Map of coastal dune sheets in Baja California (BC) and Baja California Sur (BCS), Mexico, including the large Magdalena and Guerrero Negro dune sheets (stippled pattern) and the small dune fields at San Quintin and Cabo San Lucas (arrows). The large Sonoran or Gran Desierto coastal dune sheet (Blount and Lancaster, 1990) occurs at the mouth of the Colorado River (bold line) at the northern end of the Gulf of California. Locations of four other major dune sheets are shown in the U.S.A. Pacific Coast (solid circles in map inset) (Cooper, 1958, 1967). The west coast continental shelf break in in the Baja Peninsula, is shown at the 200 m depth bathymetric contour (dashed line). The 100 m mid-shelf depth bathymetric contour is shown in Fig. 2B.

orientations and littoral transport continuities could have differed greatly from the present coastline during late Pleistocene marine low-stands. Could late Pleistocene paleo-sea levels, shoreline orientations, and paleo-wind/wave stress forcing conditions over the Baja California Sur continental shelf have combined to deliver the large quantities of littoral sand (Carranza-Edwards et al., 1998) that accumulated by eolian transport in the Magdalena and Guerrero Negro coastal dune sheets?

In this article, we present thermoluminescence and radiocarbon sample ages from shallow dune deposits in the Magdalena and Guerrero Negro dune sheets (Fig. 1) and relate the deeper sample ages ($\geq$2 m depth) of the dated dune deposit migrations to marine low-stand conditions during the last $\sim$ 70 ka (70×10^3 yr). Under the conditions of latest Pleistocene marine low-stands, $\sim$50–100 m depth below mean sea level (MSL), the paleo-shoreline orientations offshore of the Magdalena and Guerrero Negro coastal dune sheets were sufficiently oblique to modeled ocean wind/wave stress (Alder and Hostetler, 2015) to effectively trap littoral sand on the adjacent continental shelf areas. Onshore directional wind stress, established from preserved linear dune form orientations (Murillo De Nava et al., 1999) demonstrates the potential for eolian transport (southeast direction) of littoral sand across the emerged inner-shelf to produce the large Magdalena and Guerrero Negro dune sheets.

Alluvial down-cutting during lowered sea levels produced incised valleys in the dune sheet areas that were subsequently submerged during the Holocene marine transgression. The Holocene marine transgression remobilized some of the submerged inner-shelf sand deposits to supply the nearshore development of 1) extensive barrier islands and sand spits (Fryberger et al., 1990; Jiménez et al., 1994) and 2) localized migratory dune fields, located along the south side of the Guerrero Negro dune sheet.

Recent reactivation of the late Pleistocene dune deposits, located southeast of the submerged lagoons in both the Magdalena and Guerrero Negro dune sheets, has led to thin covers of Holocene sand that mantle large relict dune ridges and deflation areas in the dune sheet interiors. The results of this study help to confirm the framework model of shelf marine low-stand depocenters in supplying sand to some of the lager coastal dune sheets in the central West Coast of North America (Peterson et al., 2007, 2015).

2. Background

2.1. Magdalena and Guerrero Negro dune sheet geographic settings

The Baja California Sur Peninsula represents a complex tectonic setting with localized subsidence of the east side of the Peninsula, uplift of a central Peninsular Coast Range (500–1500 m in elevation) and the relatively relative stability of western coastal plains (0–50 m elevation) after prior fault offsetting of what is now an irregular coastline. (Fig. 1) (Angelier et al., 1981; Hausback, 1984; Woods, 1980; Dorsey and Umhoefer, 2000; Michaud et al., 2007). Small, but steep, drainages (50–100 km in length) deliver coarse sediments to the western coastal plains and coastline in numerous alluvial fans and braided channel systems of ephemeral streams. Two exceptionally large embayments (~300 km along-coast length) occur in the west coast of Baja California Sur, extending from Punta Abreojos to Cabo San Lazaro and from Punta San Carlos to Punta Eugenia. The large coastal dune sheets, Magdalena and Guerrero Negro, advanced over low-relief coastal plains near the south ends of the large embayments. The positions of both dune sheets, near the southern ends of their respective embayment's, are consistent with a southeast coastal sand transport in the region (Wright et al., 1973; Fernández-Eguiarte et al., 1992).

The semi-arid/arid coastal plains in the study area yield sparse vegetation, being presently dominated by cacti and xeric scrub (Siriana et al., 1994). The planimetric surface areas of the Magdalena dune sheet (7000 km^2) and the Guerrero Negro dune sheet (8000 km^2) are mapped on the bases of 1) arena and dunas sand units (INEGI, 1984), 2) the landward boundaries of apparent linear dune forms interpreted from recent satellite images, and 3) arbitrary seaward boundaries of the modern ocean shorelines. Southeast trending dune forms in both dune sheets reflect eolian transport to the southeast during the linear dune form development (Murillo De Nava et al., 1999; Ewing and Kocurek, 2010). Both the Magdalena and Guerrero Negro dune sheets surround submerged incised valleys and/or back barrier lagoons (Fig. 1) (Gonzalez-Zamorano et al., 2013). The Magdalena Lagoon system (Bahia Magdalena and Bahía Las Almejas) and Guerrero Negro lagoon system (Laguna Ojo de Liebre and Laguna Guerrero Negro) are protected from Pacific Ocean surf by Holocene sand spits and barrier islands. Some of the Magdalena barriers are anchored by intervening bedrock islands.

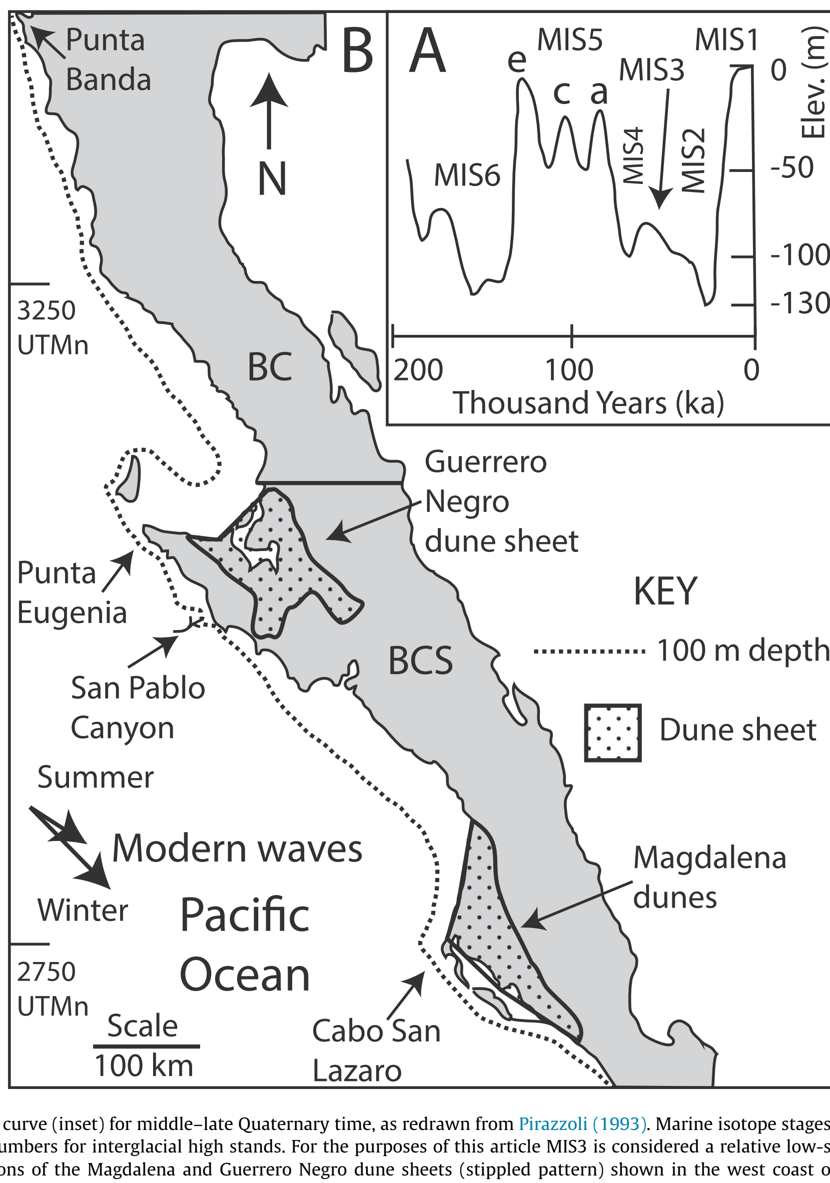

Fig. 2. (Part A) Eustatic sea level curve (inset) for middle–late Quaternary time, as redrawn from Pirazzoli (1993). Marine isotope stages (MIS) are numbered; even numbers for glacial low stands and odd numbers for interglacial high stands. For the purposes of this article MIS3 is considered a relative low-stand (mid-shelf) water depth below −50 m elevation. (Part B) Positions of the Magdalena and Guerrero Negro dune sheets (stippled pattern) shown in the west coast of Baja California Sur (BCS) with the corresponding mid-shelf bathymetric contour at −100 m elevation (dotted line).

Modern wave buoy data for the Baja California Peninsula are taken from two deep-water wave buoys, CA46065 located offshore of San Diego, California (Fig. 1) and CA46047 located 300 km northwest of San Diego (NDBC, 2016). The mean and standard deviation of significant wave height ($H_{1/3}$), reported for years 1991–2008 at buoy CA46047, are as follows: winter months (DJF) 2.5 ± 1.0 m, and summer months (JJA) 1.7 ± 0.5 m. Maximum significant wave heights for the same periods are: winter months (DJF) 6.5–8.5 m, and summer months (JJA) 3.5–4.5 m. Mean wave directions (MWD in °TN) are averaged from hourly intervals for the winter months (DJF) from both wave buoys, for a complete record 2013–2016, yielding an averaged direction of ~300° TN. Local wave heights in the Guerrero Negro study area are reported to average 2.4 m (Fernández-Eguiarte et al., 1992). Modern coastal winds in the study area vary between northerly and westerly, with reported average velocities of 4–6 m s^{-1} (Pérez-Villegas, 1989).

2.2. Paleo-sea level curves

During late Pleistocene marine low-stands (80–15 ka) eustatic paleo-sea levels fell to ~50–130 m depth below MSL (Fig. 2A). The low-stand paleo-shorelines would have developed in the middle continental shelf, ~5–50 km offshore of the present shoreline (Fig. 2B). At the lowest eustatic sea levels, the winter wave base could have dropped to −150 m elevation, providing a continuous corridor of littoral sand transport from Punta Banda to the Guerrero Negro dune sheet, a southwest coastline distance of 500 km. It is not known if sand was transported south around the Punta Eugenia headland and then beyond the San Pablo submarine canyon head to the Magdalena dune sheet during the lowest marine stands. The coastline segment extending south of Punta Eugenia represents another 350–400 km distance of potential southeast sand transport along the mid-continental shelf to the Magdalena dune sheet.

3. Methods

Shallow morpho-stratigraphic sections (2–10 m depth subsurface) in the Magdalena dune sheet (n = 11) and Guerrero Negro dune sheet (n = 11) were measured in trenches, auger boreholes, excavated borrow pits, and alluvial valley/gully cut exposures. Measured section sites were selected to ground truth the interpreted areal extents and relative ages of dune deposits in the dune sheets, as based on 1) geologic/ topographic maps (INEGI, 1984) and 2) satellite images (Figs. 3 and 4). The morpho-stratigraphic sections were measured for 1) deposit type, 2) sand grain size using a CANAM Stratigraphic grain size card, 3) soil color using a Munsel color chart, 4) soil structure nomenclature as based on Birkeland (1999), and 5) unconfined shear strength (kg cm^{-2}) using a calibrated penetrometer (Peterson et al., 2006). Sand grain

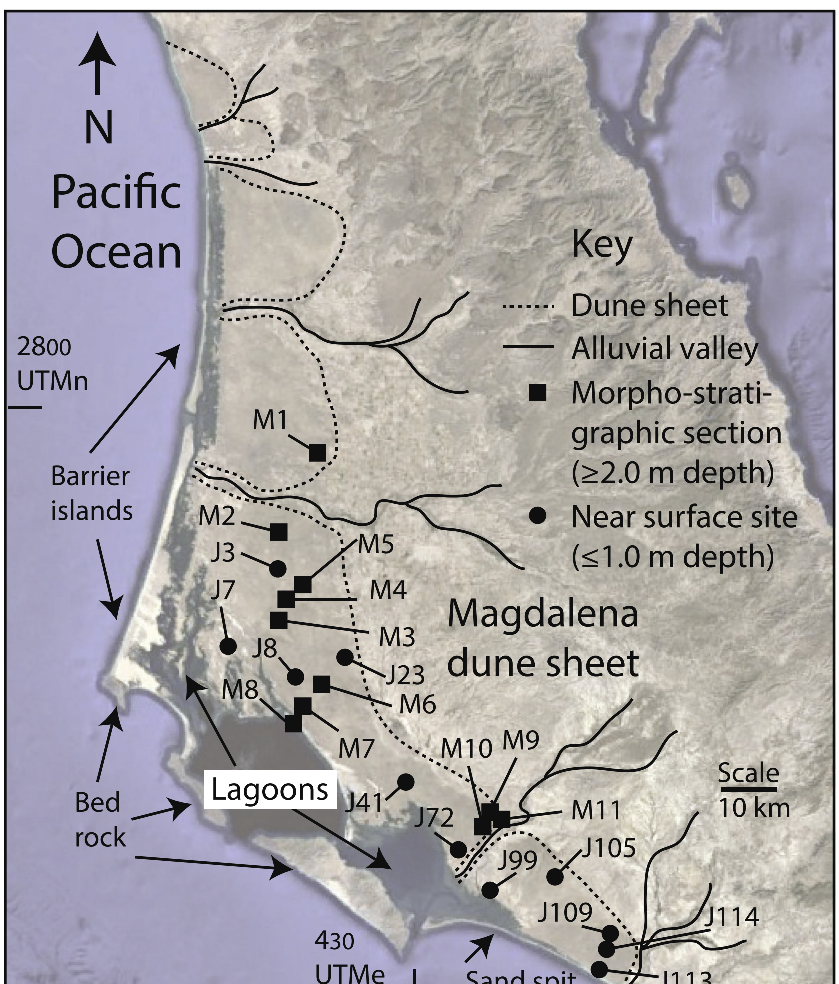

Fig. 3. Map of morpho-stratigraphic sections (M) in solid squares (Peterson et al., 2006) and selected near surface sites (J) in solid circles (Murillo De Nava et al., 1999) in the Magdalena dune sheet. The pre-Holocene dune sheet (dashed line) extends landward of submerged Bahia Magdalena lagoons (dark shading), which are bordered on their seaward sides by barrier sand islands, bedrock islands, and sand spits.

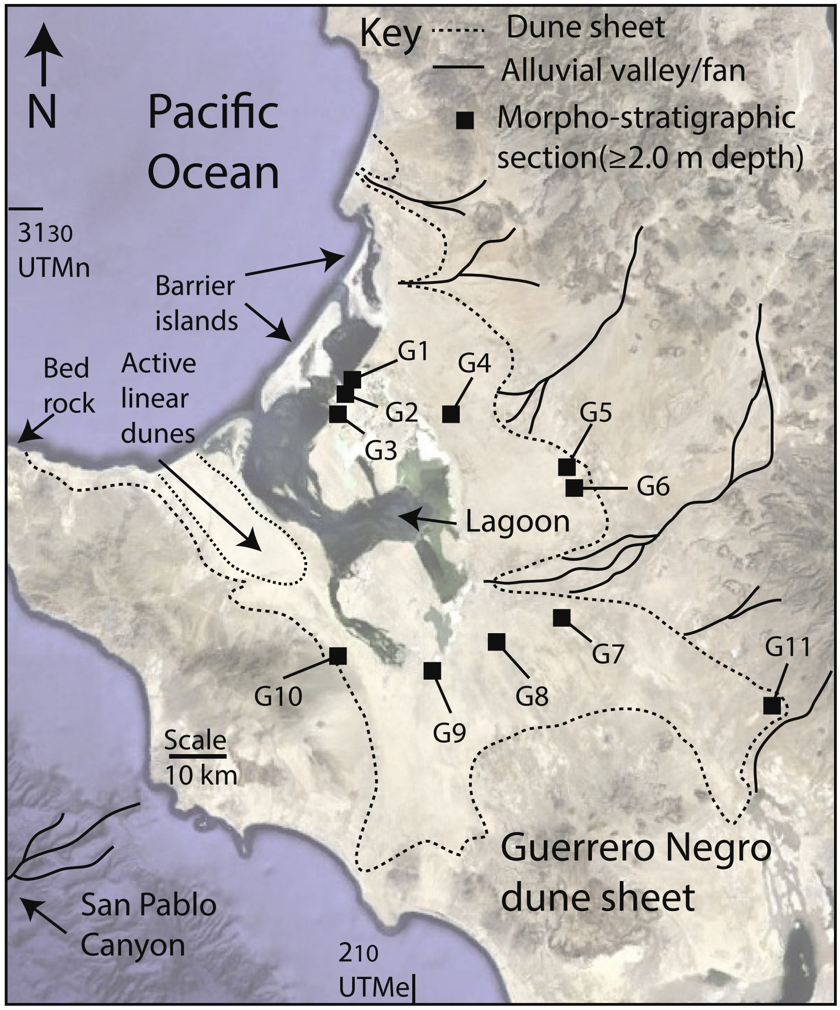

Fig. 4. Map of morpho-stratigraphic sections (G) in solid squares (Peterson et al., 2006) in the Guerrero Negro dune sheet. The pre-Holocene dune sheet (dashed line) extends landward of submerged lagoon (Laguna Ojo de Liebre), which is bordered on its seaward side by Holocene barrier islands. Active linear dunes (dotted line) extend landward of the modern beach at the south end of the Guerrero Negro dune sheet.

sizes are as follows, very fine lower (vfL) 6–88 μm, very fine upper (vfU) 88–125 μm, fine lower (fL) 125–177 μm, fine upper (fU) 177–250 μm, medium lower (mL) 250–350 μm, medium upper (mU) 350–500 μm, and coarse lower (cL) 500–710 μm. Measured section positions, estimated elevations, and geomorphic settings are presented in Table 1. Examples of soil profiling, including accumulation horizons and representative cementation, are shown in Fig. 5A and B.

Ten morpho-stratigraphic sections were selected for new thermoluminescence dating (TL) and radiocarbon dating (^{14}C) of dune deposits in the Magdalena and Guerrero Negro dune sheets. TL dating is a proven method for reconnaissance dating of dune sheet sand deposits, which, by the nature of their extensive eolian transport origins, are assumed to have been fully reset by sun light prior to deposition (Aitken, 1985). Extended descriptions of the TL methods used, and laboratory results obtained, for the 10 new TL samples used in this article are presented elsewhere (Peterson et al., 2006). Seven TL ages that are used in this study were collected from near surface (≤1.0 m depth) cores, scarps, and/or trenches in the Magdalena dune sheet, as previously reported by Murillo De Nava et al. (1999). One new ^{14}C shell age from an exposed bay cliff (site M8) in the Magdalena dune sheet (Fig. 3) is used to supplement four selected ^{14}C shell ages from near surface sample sites (≤1.0 m depth), as previously reported by Murillo De Nava et al. (1999).

The ^{14}C ages reported in this article are estimated to the nearest ±0.1 ka, for the purposes of comparison to TL ages, paleo-sea level data, and paleo-wind/wave forcing data, which are reported in ka. The original ^{14}C laboratory analytical results are available in Murillo De Nava et al. (1999) and Peterson et al. (2006). The TL laboratory data for Magdalena dune sheet sites MM1, M2, M3, M4, M6, M7 and M10 and Guerrero Negro dune sheet sites G5a, G5b, G6, and G11 are also shown here in the Table: TL Laboratory Results, presented in Supplementary Materials.

Sampling of the Magdalena and Guerrero Negro dune deposits for soil development profiling and TL dating proved to be problematic. Sampling problems included very dry sand at the surface and indurated caliche soil layers in the subsurface. Water was used to dampen and temporarily stabilize dry sand in hand drilled auger holes (2–4 m depth subsurface) in the Magdalena dune sheet. Deeper morpho-stratigraphic sections were sampled in the Guerrero Negro dune sheet (Fig. 4), where they were exposed in construction borrow pits (G4, G5) and alluvial valley or gully cuts (G9, G10, G11).

Preliminary field observations in the study area showed thin deposits of uncemented dune sand over thicker cemented dune deposits (Fig. 5). Some of the uncemented sand deposits contained 1) rounded caliche fragments, 2) winnowed Fe-rich peds or soil concretions, and 3) animal burrows ~1.0 m depth subsurface, demonstrating origins from the eolian/bioturbation mixing of

Table 1
Settings, positions, and elevations of morpho-stratigraphic sections.

Section No.	UMTn (m)	UTMe (m)	Elev. (m)	Setting
M1	2789780	411780	40	Eastern margin of dune sheet.
M2	2774010	404560	35	Linear dune ridge (SE) 5–10 m height.
M3	2757980	405580	30	Linear dune ridge (SE).
M4	2756710	405110	35	Linear dune ridge (SE) 5–10 m height.
M5	2762450	408790	50	Deflation hollow.
M6	2742450	410680	20	Linear dune ridge (SE) 5–10 m height.
M7	2738550	407150	40	Western edge of linear dune ridge plateau
M8	2738030	405440	10	Bay cliff up to ~7 m height above tide line.
M9	2716050	447030	35	Eastern extent of linear dune ridges
M10	2715630	446450	45	Linear dune ridge (SE) 5–10 m height.
M11	2714660	449850	55	Dune hummocks over alluvial terrace.
G1	3096830	787850	5	Dune deflation surface above marine terrace.
G2	3092230	785010	5	Eastern edge of Holocene barchan dunes.
G3	3090070	784480	10	Holocene barchan dune field.
G4	3089280	216260	25	Quarry in deflation hollow in linear dune field.
G5	3077790	240610	60	Test pit in linear dune ridge (SE) 3–5 m height.
G6	3077750	240810	60	Crest of linear dune ridge (SE) 2–5 m height.
G7	3048750	238020	30	Active dunes 2–4 m height over deflation plain.
G8	3044190	225220	35	Active linear dunes (SE) 2–3 m height over Pleistocene dune deflation surface.
G9	3039770	213250	15	Alluvial valley cut in dunes adjacent to lagoon.
G10	3037700	789800	25	Alluvial valley cut in liner dune field.
G11	3032640	280220	80	Southeastern extent of dune field, alluvial cut.

Notes: Morpho-stratigraphic sections are from the Magdalena (M) and Guerrero Negro (G) dune sheets. Section site coordinates are in UTM meters (estimated potential errors ~ 10 m). UTM zones include 11 R and 12 R (Guerrero Negro dune sheet) and 12 R (Magdalena dune sheet).
Elevation relative to mean sea level (MSL) is estimated to the nearest 5 meters using GPS position data and GIS-DEM. Linear dune ridge crest heights in meters (m) above intervening valley bottoms were visually estimated on-site using scaled staffs and levels. Linear dune trends to the southeast (SE) are taken from site satellite images (Google Earth, 2016).

pre-existing cemented dune soils. Test auger holes were drilled, sampled, and logged in daylight to establish subsurface depths to the cemented dune deposits that contained Bk or K (caliche) soil accumulation horizons (Birkeland, 1999) and/or high penetrometer (P) values ($\geq$2.5 kg cm^{-2}) of recovered soil fragments. Unexposed TL samples in adjacent auger holes were obtained from target horizons in the uncemented and cemented dune deposits.

Dune soil chronosequences were established from measured soil profile parameters, as measured at sites M1, M2, M4, M5, M6, M7, M8, and M10 in this study and at sites 3, 18, and 23 from Murillo De Nava et al. (1999) in the Magdalena dune sheet (Fig. 3). The chronosequence parameters include 1) the absence or presence of soil caliche horizons (Birkeland, 1999) and 2) penetrometer resistance of the soil parent and accumulation horizons relative to corresponding dune soil ages (Peterson et al., 2006). The soil chronosequences were used to discriminate uncemented (Holocene) dune deposits from cemented (late Pleistocene) dune deposits in the study area.

Representative linear dune forms were mapped in GIS coverages for the Magdalena dune sheet and Guerrero Negro dune sheets, respectively, using Google Earth (2016) satellite images from 11/09/2009–10/18/2014 and 1/31/2009–6/22/2016. For example, dune ridge lineations are shown between sites G7, G8, and G9 in the Guerrero Negro dune sheet (Fig. 4). The satellite images were examined at relatively-low eye altitudes of 5–10 km, using natural hill slope shading and vegetation patterns to establish dune ridge and valley alignments relative to true north (°TN). Goundtruthing at morpho-stratigraphic section sites (Figs. 3 and 4) in both the Magdelena and Guerrero Negro dune sheets established the vertical relief (2–10 m from ridge crest to deflation trough) of the linear dune forms using scaled staffs and levels.

4. Results

In this section, shallow morpho-stratigraphic sections (1–9 m depth subsurface) are shown from the Magdalena and Guerrero Negro dune sheets (Figs. 3 and 4) to demonstrate the vertical sequences of uncemented dune deposits over cemented dune deposits. Representative sand grain sizes, paleosols, and unconfined shear strengths (penetrometer) are summarized in the morpho-stratigraphic sections (this article) from previously reported core logs (Peterson et al., 2006). Both TL and ^{14}C ages from the morpho-stratigraphic sections and from near surface samples (Murillo De Nava et al., 1999) are presented in this section to constrain the ages of the uncemented and cemented dune deposits.

4.1. Morpho-stratigraphic sections in the Magdalena dune sheet

Nine of the 11 shallow morpho-stratigraphic sections in the Magdalena dune sheet include uncemented dune deposits (generally <2.0 m depth subsurface) overlying cemented dune deposits (Fig. 6). The uncemented dune deposits are characterized by medium –to- fine sand with low unconfined shear strengths (P $\leq$ 2.0 kg cm^{-2}), and a lack of caliche (Bk or K) paleosol horizons. The cemented dune deposits are characterized by medium –to- fine sand, higher unconfined shear strengths (P $\geq$ 2.5 kg cm^{-2}), and the presence of caliche (Bk or K) paleosols. Dry colors of the uncemented dune deposits, 10YR7/3 (M1) and 10YR6/3 (M10) are lighter than those recorded in the cemented dune deposits, 10YR4/4 (M1), 10YR5/3 (M6), 10YR5/4 (M7), and 10YR5/5 (M10). All the analyzed dune deposits from the Magdalena dune sheet showed redder hues (10YR), from Fe-staining, than modern 'unweathered' beach sand (2.5Y) in the study area. Deeper sampling of basal dune/alluvial deposits in Magdalena dune sheet will require mechanical drilling to penetrate the indurated caliche (K) layers.

4.2. TL and ^{14}C dating of dune deposits in the Magdalena dune sheet

Five new TL ages from cemented dune deposits in the Magdalena dune sheet (1.7–2.3 m depth) ranged from 22.5 ± 2.7 ka –to- >59.1 ± 3.8 ka. Five of the cemented dune deposit sections were from large linear dune ridges (Table 1), including the TL-dated late Pleistocene sections at sites M2, M6, and M10. Two additional TL

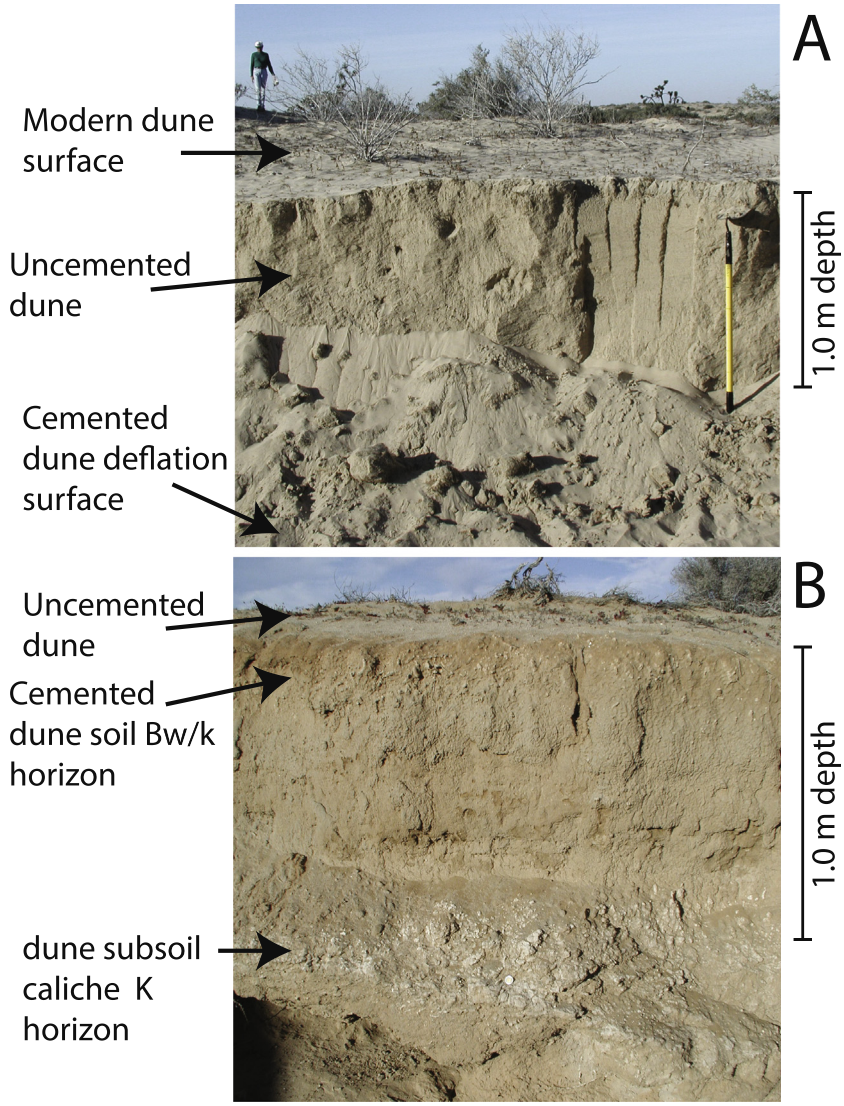

Fig. 5. (Part A) Dune soil exposed in a trench/auger site in the Guerrero Negro dune sheet (site G6), showing recently-active dune deposits (0–100 cm depth). The uncemented dune deposits contained winnowed peds and rounded caliche fragments from pre-existing Pleistocene dune soils. Hand augering at site G6 reached indurated or cemented dune paleosols at depths of 150–200 cm below surface. (Part B) Soil development in a linear dune ridge, as exposed in a test pit in the Guerrero Negro dune sheet (section site G5). The soil profile shows loose Holocene dune sand at the surface, over a weakly-cemented late-Pleistocene Bw/k paleosol horizon, over a well-cemented subsoil K (caliche) horizon. The subsoil K horizons prevented penetration by hand augering methods. See Fig. 4 for site positions.

ages (44.7 ± 12 ka and 72.5 ± 18.6 ka) are shown from site J23 at depths of ~ 1.0 m subsurface (Murillo De Nava et al., 1999). Near surface samples (J) from very-shallow dune deposits (≤1.0 m depth subsurface) in the Magdalena dune sheet span the Holocene period, ranging in age from 10.5 ± 1.6 ka –to- 0.41 ± 0.05 ka. One of the morpho-stratigraphic sections (M8) from the Magdalena dune sheet contained an uncemented dune deposit of ~5.0 m thickness (Fig. 6). Marine shells from the uncemented dune sand section (~1.5 m depth subsurface) at site M8 were ^{14}C dated to 3400–3800 cal BP (~3.62 ± 0.18 ka) (Table 2). It is assumed that the large shell fragments (up to 10 cm diameter) were transported from the adjacent lagoon (Fig. 3) by mammalian, avian and/or other scavengers.

4.3. Morpho-stratigraphic sections in the Guerrero Negro dune sheet

Measured dune deposits in 11 morpho-stratigraphic sections from the Guerrero Negro dune sheet range from 1 –to- 8 m in thickness (Fig. 7). Cemented dune deposits (P 2.0–4.5 kg cm^{-2}) were overlain by uncemented dune sand (P 0.5–1.0 kg cm^{-2}) in eight of the morpho-stratigraphic sections. Only one uncemented dune section (M3) exceeds 3.0 m in thickness. It occurs in an active barchan dune field (~1.0 km in width), located across from a shallow tidal/eolian flat (Fig. 4), which extends inshore from an offshore barrier island (Fryberger et al., 1990). Much larger fields of active/recently active linear dunes (5–10 m in height) extend ~30 km southeast of the modern beach at the south side of the Guerrero Negro dune sheet. No morpho-stratigraphic auger sections were obtained from those active dune fields. The dune field deposits from the south side of the Guerrero Negro dune sheet are exposed at the coast where active/uncemented dunes (3–7 m thickness) overlie cemented dune deposits (5–10 m thickness) in exposed sea cliff sections.

Unlike the large active dune fields along the south side of the Guerrero Negro dune sheet, the cemented dune deposits located landward of the Guerrero Negro lagoon system (G5–G10) are mantled by only thin veneers of uncemented dune deposits (1.0–3.0 m thickness). No uncemented dune deposits occurred in the most

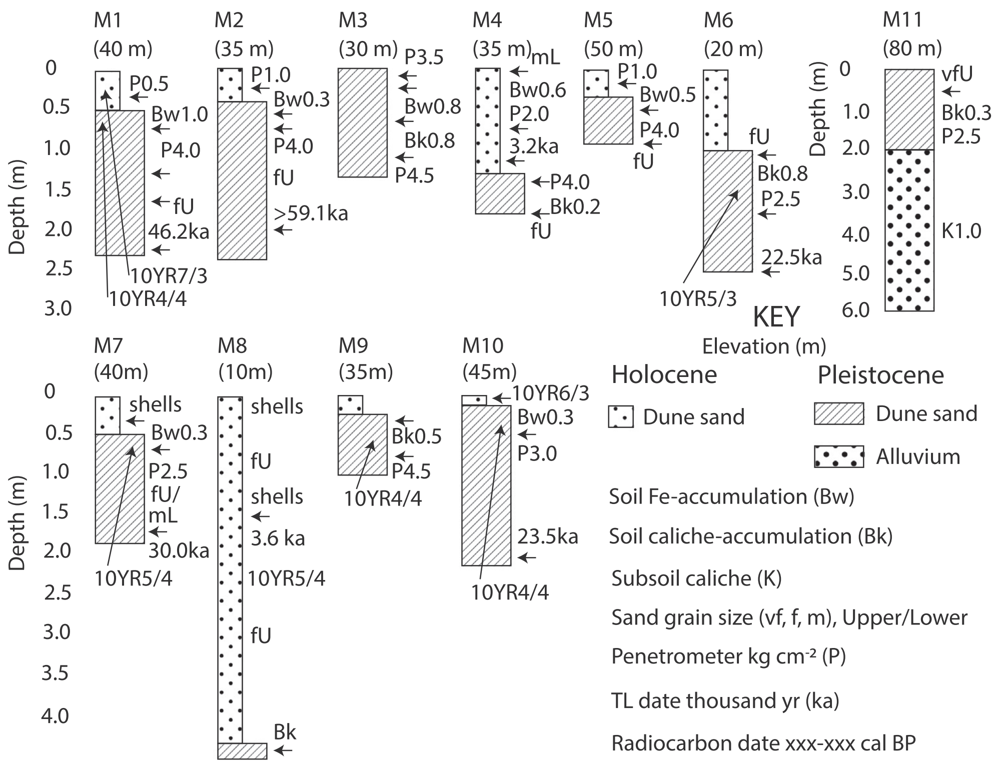

Fig. 6. Morpho-stratigraphic sections from the Magdalena dune sheet. Sand grain sizes include very fine (vf), fine (f), and medium (m). Unconfined shear strengths are from a penetrometer (kg cm^{-2}). TL and ^{14}C ages are shown in Table 2. Section site positions are shown in Fig. 3 and Table 1.

Table 2
TL and ^{14}C ages from the Magdalena and Guerrero Negro dune sheets.

Dune sheet	Age/Date type Sample/Lab No.	Depth (m)	Age (ka)	Ref.
Magdalena				
M1	TL (W3594)	2.3	46.2 ± 5.8	(1)
M2	TL (W3180)	2.0	>59.1 ± 3.8	(1)
M4	TL (W3181)	1.2	3.2 ± 0.3	(1)
M6	TL (W3595)	2.5	22.5 ± 2.7	(1)
M7	TL (W3596)	1.7	30.0 ± 2.9	(1)
M10	TL (W3597	2.0	23.5 ± 1.4	(1)
M8	^{14}C (B191887)	1.5	3.62 ± 0.18	(1)
J3	TL	0.5	10.5 ± 1.6	(2)
J7	TL	0.5	4.7 ± 0.7	(2)
JSite23a	TL	1.0	72.5 ± 18.6	(2)
JSite23b	TL	1.0	44.7 ± 12	(2)
J41	TL	0.5	8.8 ± 0.9	(2)
J105	TL	0.5	8.7 ± 1.5	(2)
J114	TL	0.5	4.4 ± 0.7	(2)
J72	^{14}C	0.2	0.41 ± 0.05	(2)
J99	^{14}C	0.4	5.35 ± 0.9	(2)
J109	^{14}C	0.6	0.97 ± 0.05	(2)
J113	^{14}C	1.0	4.92 ± 0.08	(2)
Guerrero Negro				
G5a/TL	TL (W3178)	1.8	>60.4 ± 4.9	(1)
G5b/TL	TL (W3179)	2.7	99.8 ± 9.4	(1)
G6/TL	TL (W3398)	1.5	0.7 ± 0.05	(1)
G11/TL	TL (W3593)	1.5	20.7 ± 2.1	(1)

Notes: Positions and elevations of TL and ^{14}C dated morpho-stratigraphic sections, M and G, respectively from the Magdalena and Guerrero Negro dune sheets are presented in Table 1 and are shown in Figs. 3 and 4. Positions of near surface sites (J) are shown in Murillo De Nava et al. (1999) and in Figs. 3 and 4. Specimen lab numbers that are presented in this article are TL (W) for University of Wollongong and ^{14}C (B) for Beta Analytic Inc. For specimen details from Reference (2) see Murillo De Nava et al. (1999). Sample depths are in meters subsurface. TL ages are in ka ±1 Std Dev. ^{14}C ages are converted to ka (±1 Std Dev) from calibrated ages provided in Murillo De Nava et al. (1999). A new shell ^{14}C age (7.5 cm pelecypod valve) from site M8 is reported here as follows: conventional radiocarbon age 3910 ± 60 BP, with marine reservoir correction (3910 ± 60 BP) and 2sig calibration 3440–3800 cal BP from Beta Analytic (B191887), using INTCAL 98. Laboratory methods and analytical details about sample TL and ^{14}C dating are provided in corresponding references (1) Peterson et al. (2006) and (2) Murillo De Nava et al. (1999). Laboratory TL data are provided in a table entitled TL Laboratory Results in Supplementary Materials.

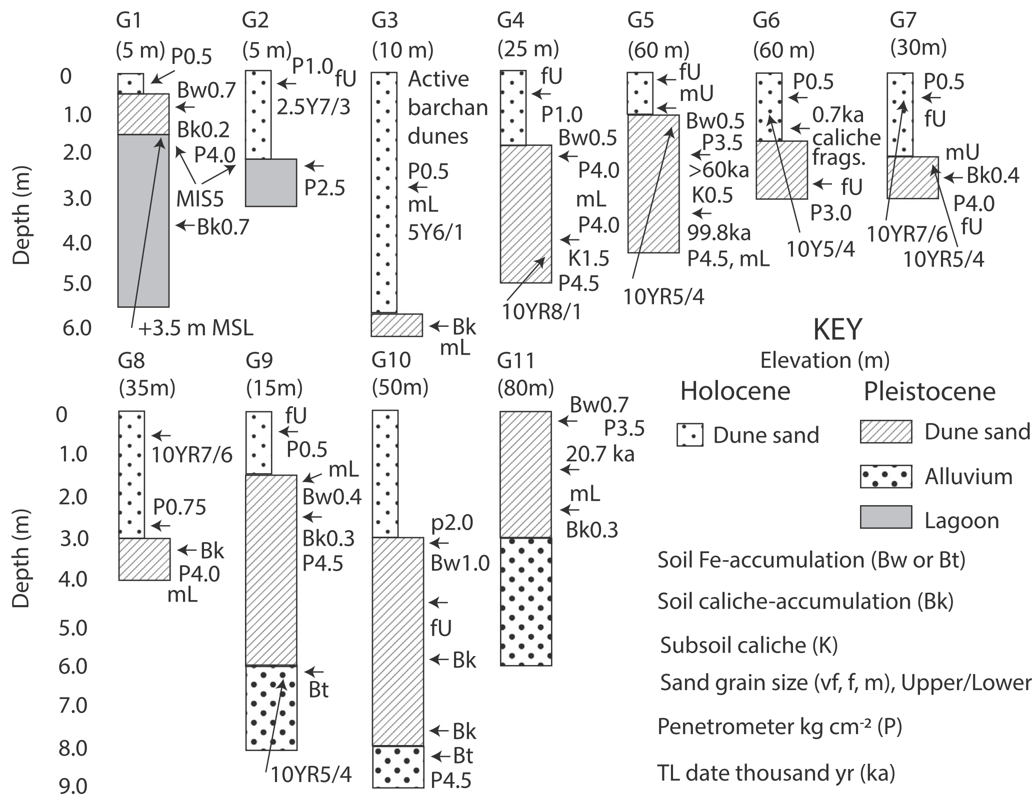

Fig. 7. Morpho-stratigraphic sections from the Guerrero Negro dune sheet. Sand grain sizes include very fine (vf), fine (f), and medium (m). Unconfined shear strengths are from a penetrometer (kg cm^{-2}). TL and ^{14}C ages are shown in Table 2. Section site positions are shown in Fig. 4 and Table 1.

landward morpho-stratigraphic section (G11) located ~100 km southeast distance from the present Pacific Ocean shoreline. Cemented dune sequences of ~5 m thickness were observed in alluvial valley cuts at sites G9 and G10 (Fig. 8A). The maximum thickness of the cemented dune deposits in the south side of the Guerrero Negro dune sheet were not established in this reconnaissance study. Mechanical drilling will be required to reach basal dune/alluvial deposits below subsoil caliche horizons in most localities of the Guerrero Negro dune sheet. The tops of six buried cemented dune sequences at sites G3, G4, G5, G7, G8, and G10 contain paleosols (Bw, Bk soil horizons) or caliche (K) subsoil horizons.

4.4. Reconnaissance TL dating of dune deposits in the Guerrero Negro dune sheet

A shallow dune deposit (1.5 m depth subsurface) from the uncemented dune deposit at G6 (0.7 ka) represents a very recent episode of dune deposition (Fig. 7 and Table 2). TL ages from the cemented dune deposits in shallow morpho-stratigraphic sections (1–3 m depth subsurface) range from 20.7 ± 2.1 ka (G11) to 99.8 ± 9.4 ka (G5). A well-developed caliche horizon (K) developed at 2.5–3.0 m depth subsurface in morpho-stratigraphic section G5 (Fig. 8B). The modest thickness (~3 m) of late Pleistocene dune deposits (~20–100 ka in age) at site G5 likely reflects episodic deflation along the north side of the Guerrero Negro dune sheet. A very-thin (~1.0 m thickness) late Pleistocene dune deposit, at site G1, is also thought to reflect deflation at the seaward side of the large dune sheet. The remnant dune deposit in G1 is underlain by cemented lagoon mud deposits (P 4.0 kg cm^{-2}). The late Pleistocene lagoon deposit, at an elevation of 2–3 m MSL, is assumed to correspond to a marine high-stand from one of the Marine Isotope Stage 5 high-stands (MIS5a,c,e) at ≥83 ka in age (Fig. 2A).

5. Discussion

In this section the dated morpho-stratigraphic sections in the Magdalena and Guerrero Negro dune sheets (Figs. 6 and 7) are compared to paleo-climate indicators of paleo-wind and -wave stress, paleo-sea levels (Fig. 3A), and corresponding shoreline orientations (Fig. 3B) to establish mechanisms of coastal sand supply during late Pleistocene and Holocene time.

5.1. Dune form indicators of coastal wind stress directions

Both modern and paleo-dune forms, including linear dune ridges, transverse dune migrations and barchan dune migrations, trend southeast in the Magdalena dune sheet (Murillo De Nava et al., 1999). Representative mapping of linear dune features in recent satellite images of the Magdalena and Guerrero Negro dune sheets (Fig. 9) confirms the southeast trends of dune forms and associated dune migrations. However, significant variations (±20°) in linear dune form bearings occur within each dune sheet. Varied topography and associated wind field stress directions could account for the local variations in dune sand migration bearings. For example, a topographic ridge redirects wind flow at the south end of the Guerrero Negro dune sheet. Variations in wind stress directions could also have varied through time, and large relict dune forms could have influenced recently reactivated dune form directional trends.

TL dated samples from shallow subsurface depths (~2.0 m depth) of large dune ridges (5–10 m in height) in the Magdalena and Guerrero Negro dune sheets yielded late Pleistocene ages (Tables 1 and 2). Linear southeast-trending paleo-dune ridges are dated at M2 (>59.1 ± 3.8 ka), M6 (22.5 ± 2.7 ka), M7 (30.0 ± 2.9 ka), and M10 (23.5 ± 1.4 ka) in the Magdalena dune sheet (Fig. 6), and G5 (>60.4 ± 4.9 ka) in the Guerrero Negro dune sheet (Fig. 7).

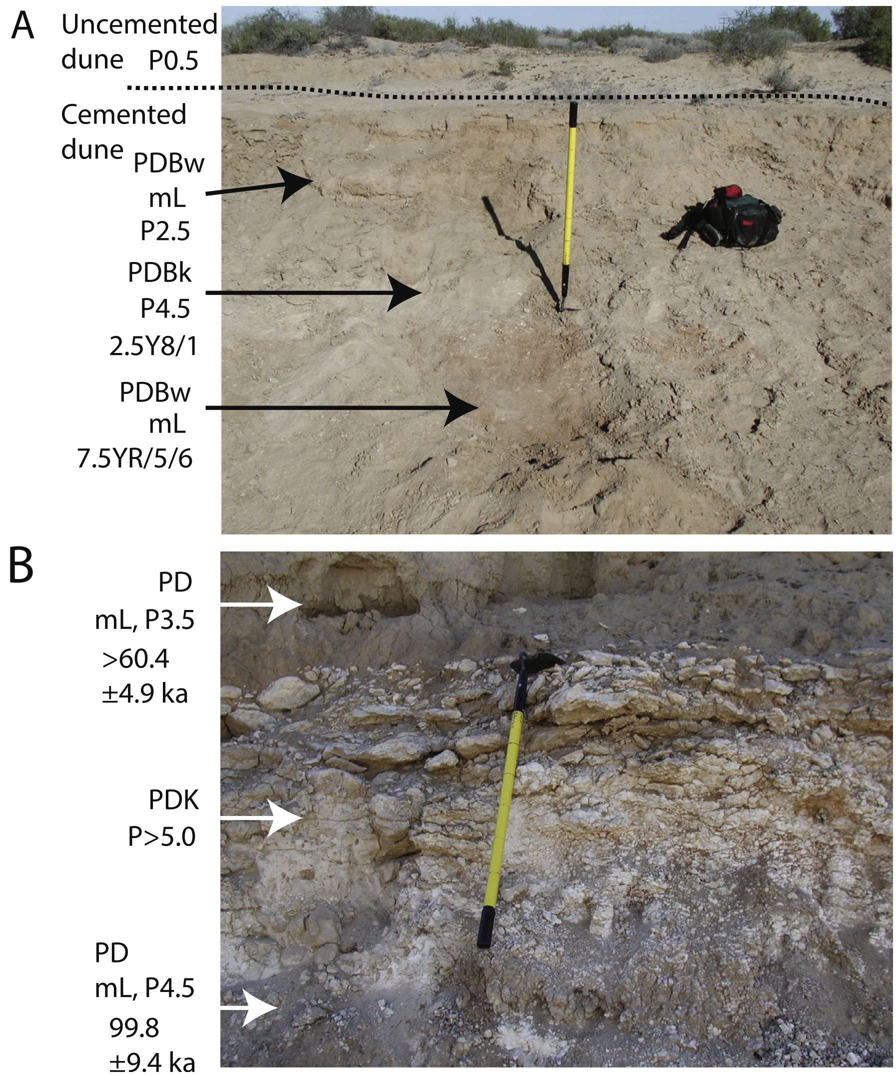

Fig. 8. (Part A) The upper three meters of morpho-stratigraphic section G9, as exposed in a gully cut in the Guerrero Negro dune sheet (see Table 1 and Fig. 4 for site location and Fig. 7 for a measured section). Uncemented or reactivated dune deposits, with a penetrometer (P) value of 0.5 kg cm^{-2} unconfined shear strength, overlie cemented dune deposits, medium low (mL) in dominant grain size, and penetrometer (P) values of 2.5–4.5 kg cm^{-2}. Weakly developed paleosols in the upper two meters of the cemented dune deposits (PD) contain weak Fe-accumulation horizons (PDBw, reddish hue 7.5YR5/6) and a weak caliche horizon (PDBk grayish hue 2.5Y8/1). Hoe handle is 1.0 m in length for scale. (Part B) The lower two meters of the morpho-stratigraphic section G5 in the Guerrero Negro dune sheet. A subsoil caliche (PDK) horizon occurs between two cemented dune deposits (PD), TL dated at >60.4 ± 4.9 ka and 99.8 ± 9.4 ka (Table 2).

Dominant onshore eolian transport in both the Magdalena and Guerrero Negro dune sheets (Fig. 9) was to the southeast throughout the period of preserved dune ridge deposition (60–0 ka).

The estimated means of representative large linear dune ridges in late Pleistocene dune sheet interiors, located landward of the submerged lagoons (Fig. 9) in the Magdalena and Guerrero Negro dune sheets, respectively, are ~120° TN and 140° TN. Reversing and extrapolating late Pleistocene directions of eolian transport directions across the offshore inner-shelf (average bearing ~310° TN) places potential offshore sources of littoral sand to the northwest of each dune sheet centroid. Were the corresponding paleo-shoreline orientations during late Pleistocene time capable of delivering sand to those projected regions offshore of the Magdalen and Guerrero Negro dune sheets? This question is addressed below following a discussion about late Pleistocene wind/wave stress directions in the study region.

5.2. Modeled late Pleistocene North Pacific Ocean wind/wave stress

In this article, Holocene and late Pleistocene wave directions in the Baja California Sur study area are estimated using paleo-sea level pressure gradients and corresponding wind stress vectors that have been modeled for the NE Pacific Ocean. The paleo-sea level pressure gradients are from the GENMOM model (Alder and Hostetler, 2015), which uses outputs from the GENESISv3 atmospheric model (Alder et al., 2011) and the MOMv2 oceanic model (Pacanowski, 1996). The GENMOM model outputs are used to produce seasonal sea-level-pressure equilibrium 3 ka time slices. Mean winter wave direction (MWD) data for the study region during the last several years, 2013–2016 (~300 °TN) are presented above in Section 2.1 (Fig. 2B). The winter waves are substantially larger, both in mean and maximum significant wave heights than the summer waves. For the purposes of this article, the paleo-sea level pressure gradients from the GENMOM model winter month (DJF) outputs are used to estimate deep-water winter wave directions for the study area at times of 0, 6, 9, 12, 15, 18, and 21 ka (Fig. 10).

As shown in Fig. 10 the dominant wind stresses in the Northeast Pacific Ocean are associated with the North Pacific Low Pressure Area (NPLPA), defined here by the 995–1005 hPa surface pressure contours. Ocean surface waves produced by high-velocity winds

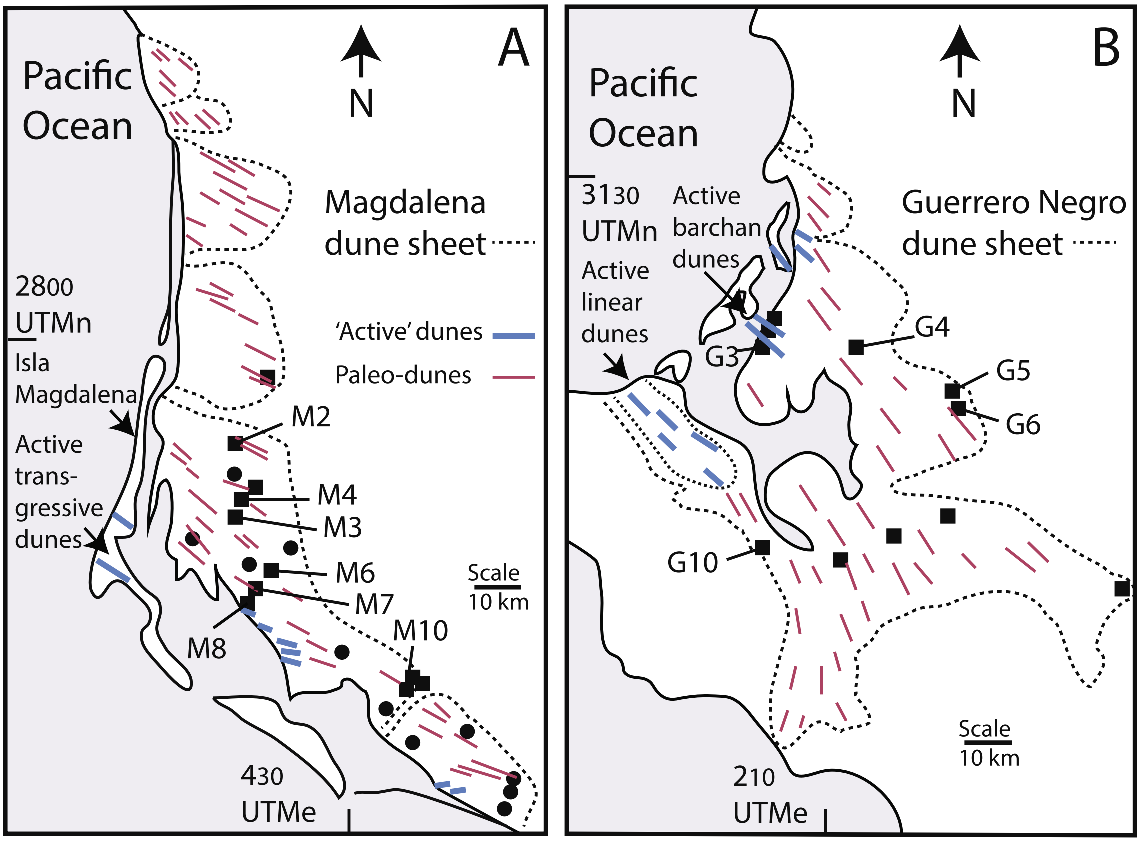

Fig. 9. Dune form wind-stress orientations (lines) are from linear dune ridges/valleys and/or transverse dune migration tracks (trending southeast) that are apparent in satellite images (see Methods). Active/recently active (little to no vegetation) dune fields, (blue bold lines) are differentiated from sparsely vegetated, paleo-dune deposits (red thin lines). Numbered sites are from morpho-stratigraphic sections where southeast-trending linear, transverse, or barchan dune forms were observed during on-site surveys (Table 1). All site numbers are identified in Figs. 3 and 4. Topographic features locally redirected wind flow to the south at the southwest arm of the Guerrero Negro dune sheet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the NPLPA propagate in straight lines, with those reaching the Baja California Sur study area following a general southeast trajectory. The relative position of the NPLPA changed slightly over time (21–0 ka). This shift was not significant in the Baja California Sur area, due to its substantial distance south of the NPLPA, but it was important for more northerly coastlines along the west coast of the USA (Peterson et al., 2007, 2015). For the purposes of this article a deep-water wave direction of ~300° TN is used for the Holocene and latest Pleistocene time periods.

5.3. Shelf bathymetry, paleo-shoreline orientations, and littoral transport

During the period of dated late Pleistocene dune migrations (70–20 ka) in the Magdalena and Guerrero Negro dune sheets (Table 2), the corresponding eustatic sea levels averaged about −100 m in elevation (Fig. 2A). As noted above in Section 2.1, the lowest eustatic sea levels might have fallen to −130 m elevation with winter wave base possibly reaching −150 m elevation. These eustatic sea levels should apply to the study area, as little to no tectonic uplift is recorded by MIS5 marine terrace deposits in morpho-stratigraphic sections G1 and G2, at the west end of the Guerrero Negro dune sheet (Figs. 4 and 7). For the purposes of this article the −100 m shelf bathymetric contour is used to generally represent paleo-shoreline angles located offshore of the Magdalena and Guerrero Negro dune sheets during late Pleistocene time (70–20 ka), as shown in Fig. 11. Paleo-shoreline orientations, taken at the −100 m bathymetric contour, range from ~290° to ~10° TN offshore of the Magdalena dune sheet and from 300° to ~30° offshore of the Guerrero Negro dune sheet. The shoreline orientations located north of both dune sheets are nearly parallel to estimated deep water wave propagation (~300° TN), yielding effective alongshore transport (to the southeast), even under conditions of less oblique nearshore wave attack from shallow-water wave refraction.

Reversed eolian transport bearings for the Magdalena and Guerrero Negro dune sheets indicate that potential littoral sand sources for the dune sheets should have been located offshore of the present shorelines at bearings of ~310° TN offshore from the dune sheet centroids (Fig. 11). The −100 m paleo-shoreline orientation taken at the projected littoral sand source (bearing of ~310° TN) offshore of the Magdalena due sheet centroid is nearly orthogonal to the estimated deep-water winter wave angle. Such a relation would greatly reduce the capability of longshore currents to transport nearshore sand to the south of the mid-dune sheet area, located offshore of Cabo San Lazaro. The −100 m paleo-shoreline orientation, taken at the projected littoral sand source (bearing of ~310° TN) offshore of the Guerrero Negro dune sheet centroid is orthogonal to the estimated deep-water winter wave angle. This relation would have effectively trapped all the littoral sand, moving south by longshore transport, within the vicinity of the Guerrero Negro dune sheet. However, at extreme low-stands of sea level the winter storm wave base might have extended to −150 m elevation, thereby permitting sand transport around Isla Cedros and Punta Eugenia, or out of the Guerrero Negro paleo-embayment. It is also unknown to what extent sand was lost from the Guerrero Negro dune sheet due to eolian overland transport at the southwest arm of the Guerrero Negro dune sheet (Fig. 9).

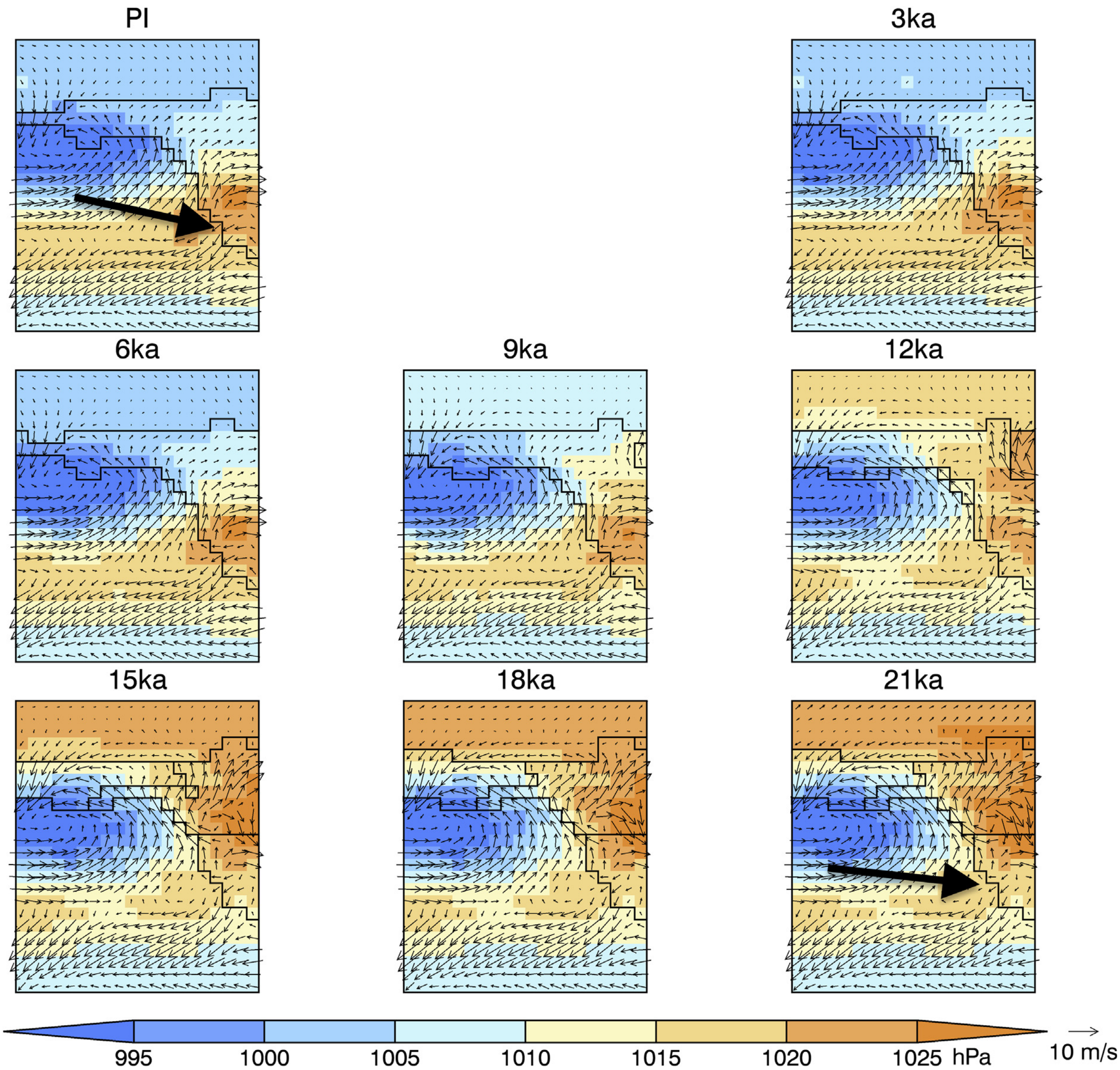

Fig. 10. GENMOM model winter month (DJF) outputs of surface pressure gradients 995 to 1025 hPa, (color/shaded scale) and associated wind vectors 0–10 m/s (arrows) for averaged time slices at 0, 6, 9, 12, 15, 18, and 21 ka. Relative wave directions are taken from a common mid-point, using the 1005 hPa surface pressure contour, to evaluate changes in estimated deep water wave direction (large arrows) between modern (PI) and 21 ka time slices. Relatively little change occurred between modern time with measured wave directions of ~300° TN and in latest-Pleistocene time at 21 ka. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In summary, the substantial changes in paleo-shoreline angles in the mid-continental shelf served to locally reduce or terminate longshore sand transport during late Pleistocene sea levels. The locally reduced or terminated longshore transport provided long-term littoral sand accumulation directly upwind of the Magdalena and Guerrero Negro dune sheets during late Pleistocene time. Late Pleistocene wind stress to the southeast transported sand in migratory dune fields across the emerged continental shelf (30–50 km in width) to the large Magdalena and Guerrero Negro dune sheets.

5.4. Holocene sand supply to barriers and lagoons from marine transgression

The barrier island and back-barrier lagoon complexes that are associated with the Magdalena and Guerrero Negro dune sheets (Fig. 12) ultimately originated from shoreward wave transport of remobilized eolian sand deposits from the middle- and inner-shelf during the Holocene (MIS1) marine transgression (Fig. 2A). No other large barrier island systems occur on the west coast of Baja California, nor were there any large rivers to source such large Holocene barrier systems, as developed seaward of the Magdalena and Guerrero Negro dune sheets (Fig. 1). Though the basal deposits of the Magdalena and Guerrero Negro barrier islands/lagoons have not been dated, the onset of marine transgressive sand supply to other large dune sheets in the West Coast of the U.S.A. began at 8.5 ± 0.5 ka (Masters, 2006; Peterson et al., 2007, 2015) following slowing of the MIS1 marine transgression in mid-Holocene time. Submergence of the lagoons, by rising sea level rise during middle-late Holocene time, would have generally precluded dune field migrations from the early proto-barrier islands to interiors of the large dune sheets on the landward sides of the large submerged lagoons. Dating of basal barrier island deposits and submerged lagoon deposits in the Magdalena and Guerrero Negro dune sheet systems will require borehole drilling, possibly 10–30 m depth below MSL to reach middle-Holocene sea level deposits (Fig. 2A).

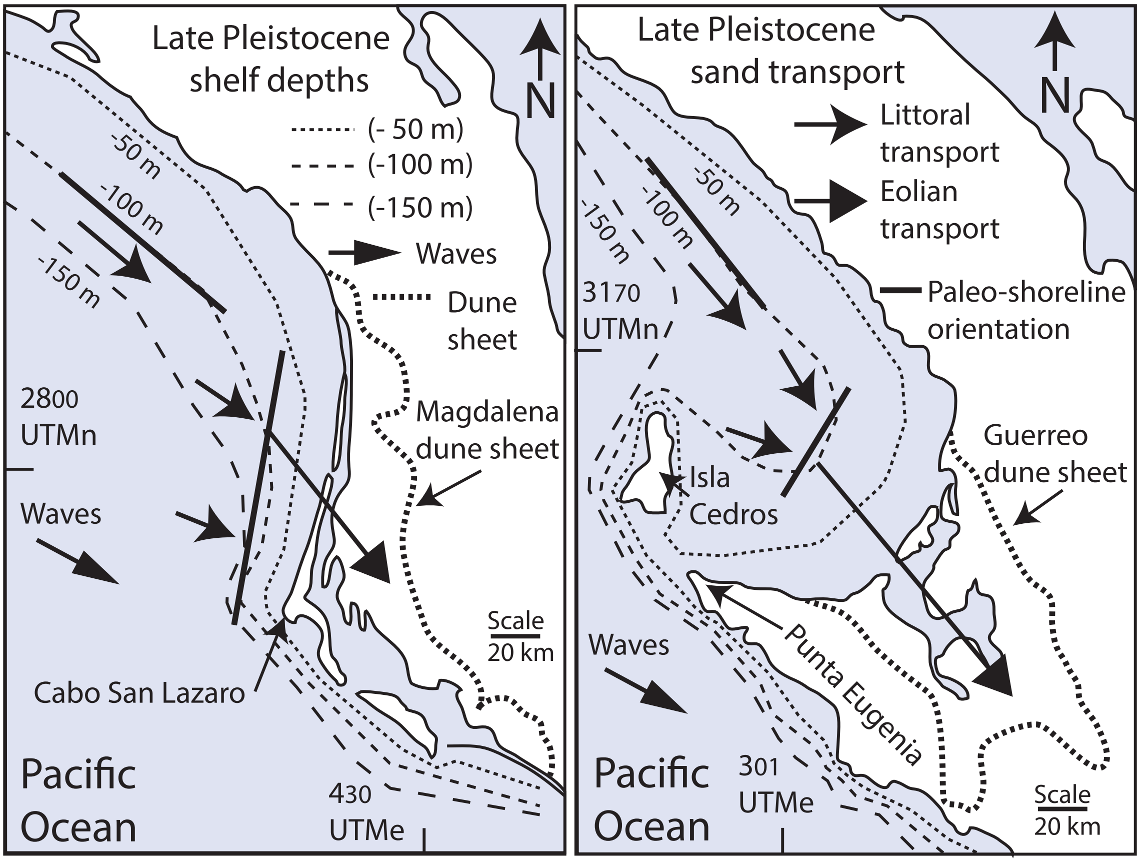

Fig. 11. Orientations of shelf bathymetric (depth) contours at −50 m, −100 m, and −150 m, relative to estimated paleo-wave direction (from ~300° TN) and eolian transport directions (towards ~130° TN). Note: deep water wave direction is reported as bearing °TN (from the ocean) but wave angle (arrow) is shown in the direction of wave propagation (towards land). Eolian transport is reported and drawn (arrow) in the direction of average paleo-dune migration. Paleo-shoreline orientations (bold lines) are taken from the −100 m contour at positions located northwest of the dune sheets.

Longshore transport likely followed further slowing of the MSI marine transgression in late Holocene time (Fig. 2A), leading to localized littoral sand accumulations in the barrier sand islands of the Magdalena and Guerrero dune sheets and at the southwest shoreline of the Guerrero Negro dune sheet (Fig. 12). Stabilization and/or possible progradation of the Isla Arena barrier island, offshore of the Guerrero Negro dune sheet, has been underway for at least 1.8 ka (Fryberger et al., 1990). The late Holocene sand supply has fed a migratory dune field extending across the Isla Arena barrier island and back-barrier tidal flats, to a westernmost late Pleistocene deflation surface (G1, G2, G3 in Fig. 7), a southeast distance of ~13 km. The extensive Holocene dune field (~30 km in southeast length) on the south side of the Guerrero Negro dune sheet (Fig. 9) has yet to be dated.

The active transverse dunes at the south end of Isla Magdalena, located offshore of the Magdalena dune sheet (Murillo De Nava et al., 1999) extend southeast (~10 km distance) across the Isla Magdalena barrier island to the back-barrier lagoon (Figs. 9 and 12). However, most of the barrier islands north of Isla Magdalena are relatively thin (0.5 km in width), demonstrating relatively little or no progradation since their initial development. Some littoral sand transport (south) around Cabo San Lazaro has likely maintained the narrow sand spits located south of Cabo San Lazaro and at Isla Creciente (Jiménez et al., 1994).

5.5. Reactivated Holocene sand cover above late Pleistocene dune deposits

Nine out of the 11 morpho-stratigraphic sections in the Magdalena dune sheet (Fig. 3) included uncemented dune deposits (0.5–5.0 m in thickness) over the late Pleistocene dune sections (Figs. 6 and 13A). The average thickness of the measured uncemented dune cover is ~1.0 m thickness, but slightly greater thicknesses occurred on the ridge slopes relative to ridge crests and the inter-dune valleys. Nine previously published near-surface samples (0.5–1.0 m depth subsurface) in the interior of the Magdalena dune sheet (Murillo De Nava et al., 1999) yielded ages with a mean and standard deviation of 5.4 ± 3.4 ka (Table 2). Most of these samples were deposited after the large lagoons (~5–10 m water depth) that border the seaward side of the dune sheet (Fig. 1) had been submerged by middle-late Holocene sea level rise (Fig. 2A). The sand source for late Holocene dunes in the interior of the Magdalena dune sheet is, therefore, limited to the eolian reactivation of pre-existing late Pleistocene dune deposits (Fig. 12). An exception to this process is reflected by the late Holocene dune deposits (~5 m thickness) in morpho-stratigraphic section M8 (Fig. 6), at the eastern shoreline of the Magdalena lagoon. Both late Holocene dunes (~3.6 ka at site M8) and modern dunes have locally developed along the lagoon shoreline, with the bay shore supply of sand increasing the active dune field widths to ~5 km in landward distance, some 10–20 km southeast of M8 (Fig. 9).

Nine of the 10 morpho-stratigraphic sections from the Guerrero Negro dune sheet interior (Fig. 4) included uncemented dune deposits (0.5–3.0 m thickness) over late Pleistocene dune sections (Fig. 7). Exceptions to these thin Holocene dune covers include 1) the large active barchan dunes at site G3, located across the lagoon from Isla Arena, and 2) the extensive fields of active or recently active linear dunes developed along the south side of the Guerrero Negro dune sheet (Fig. 12). The sources of sand to the thin Holocene dune deposits in the interior sites, located landward of the

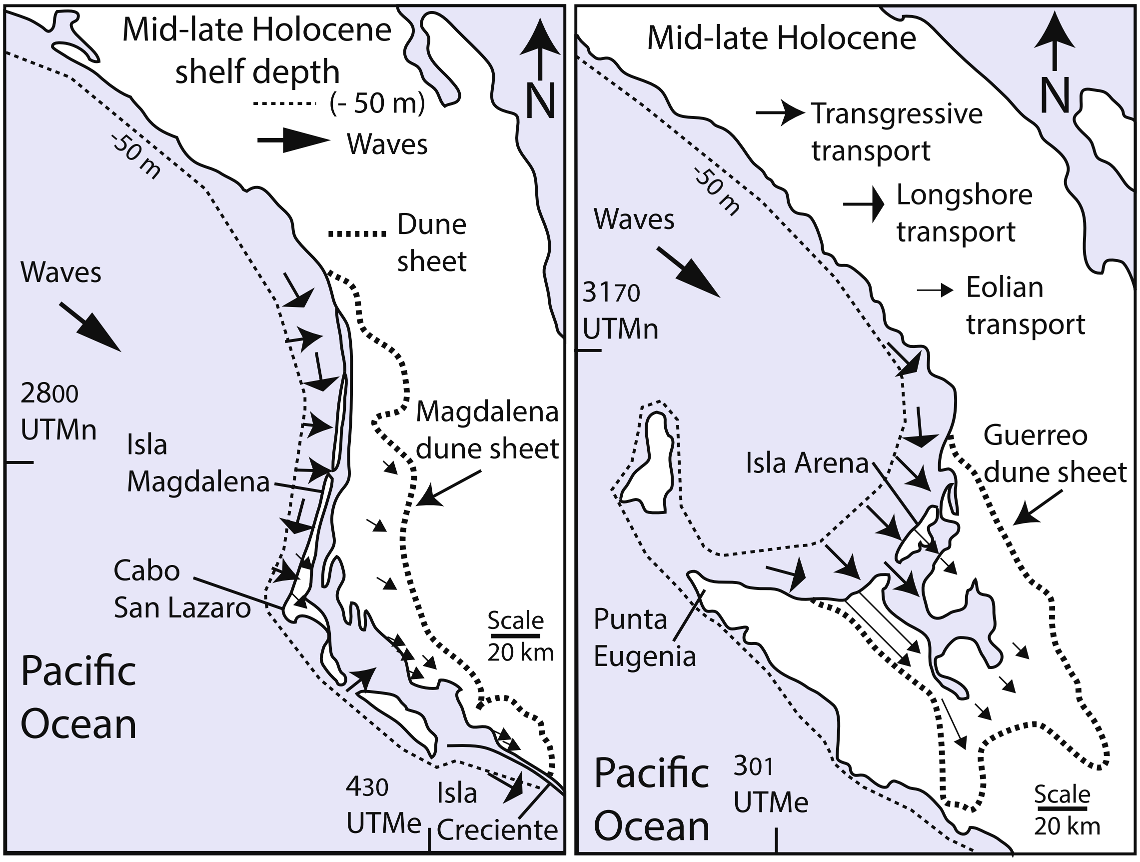

Fig. 12. The −50 m shelf depth contour represents the early Holocene sea level (paleo-shoreline) offshore of the Magdalena and Guerrero Negro dune sheets. Shoreward wave transport of shelf sand caught-up with slowing of the Holocene marine transgression in mid-Holocene time (Fig. 2A) to deliver surplus sand to the nearshore areas of the Magdalena and Guerrero Negro dune sheets. Subsequent longshore transport in late Holocene time continued to feed barrier islands offshore of both dune sheets and onshore migratory dune fields in the Guerrero Negro dune sheet (Fig. 9). Reactivation of late Pleistocene dune deposits lead to thin, but wide-spread, Holocene dune cover (short arrows) in both the Magdalena and Guerrero Negro dune sheet interiors.

large submerged Guerrero Negro lagoons, are thought to be from the reactivation of the late Pleistocene dune deposits. Such origins are confirmed by winnowed laminae of rounded reddish-hue peds (concretions) and grayish caliche granules (1–2 mm diameter) in some Holocene dune cover sections.

In summary, active migratory dunes at the south end of Isla Magdalena, and along the east shore of the Magdalena Lagoon, in the Magdalena dune sheet trend southeast (Murillo De Nava et al., 1999), as do the active dunes along the south side of the Guerrero Negro dune sheet (Fig. 9). There is relatively little difference in directional wind stress between late Holocene time and late Pleistocene time in the Magdalena and Guerrero Negro dune sheets. The thin covers of Holocene dune deposits in the interiors of the Magdalena and Guerrero Negro dune sheets owe their origins to the localized and episodic reactivation(s) of pre-existing late Pleistocene dune deposits in the dune sheet interiors. Additional work is needed to establish whether the predominance of soil Bw and Bk horizons at or near the tops of the buried late Pleistocene dune deposit sections (18 out of 20 sections) (Figs. 6, 7 and 13B) are due to 1) periods of pre-Holocene dune field stabilization or 2) eolian deflation downwards to the semi-indurated Bw/Bk horizons, prior to the Holocene dune cover deposition.

6. Conclusions

Two large dune sheets, Magdalena and Guerrero Negro, on the Pacific Ocean coast of Baja California Sur, Mexico, originated from continental shelf depocenters during late Pleistocene marine low-stand conditions. Paleo-shoreline orientations, relative to predicted late Pleistocene deep-water wave directions, permitted the localized accumulation of littoral sand in the mid-shelf to the northwest of the onshore dune sheet centroids. Prevailing coastal wind stress (to the southeast) transported the surplus littoral sand across the emerged mid-inner shelf areas (30–50 km downwind distance) to develop the onshore dune sheets between 72 and 20 ka, over low-elevation coastal plains. Alluvial valleys, which apparently dissected the large dune sheets during marine low-stand conditions, were submerged by rising sea levels during the Holocene marine transgression. Holocene submergence of the middle-inner shelf terminated eolian across-shelf sand supply during the early phase of marine transgression. Shoreward wave transport, following slowing of the marine transgression in middle Holocene time, likely delivered surplus sand to the dune sheet nearshore areas, permitting the development of barrier islands and sand spits that developed seaward of the large dune sheets. In late Holocene time, longshore transport likely continued to supply sand to the barrier islands, including some active eolian dune fields that cross the low barrier islands to reach back-barrier lagoons. Episodic reactivation(s) of late Pleistocene dune deposits in the dune sheet interiors, located landward of the submerged lagoons, permitted generally thin, but wide-spread, deposition of Holocene dune cover over late Pleistocene deposits in the Magdalena and Guerrero Negro dune sheets. This study addresses the latest-Pleistocene dune deposits in the two study areas but not the onset or basal ages of the dune sheets. Mechanical drilling

Fig. 13. (Part A) Very-large linear dune forms (10 m vertical height and 0.25–0.5 km spacing), with linear dune ridges trending southeast, as shown orthogonal to photo view direction (NE) in the Magdalena dune sheet, between sites M6 and M7 (Fig. 3). Three ridge crests are shown at arrows, with the middle ridge high-lighted by the dashed line. Reactivated and/or bioturbated sand cover (~1 m in thickness) overlies the late-Pleistocene dune ridges, as profiled and dated in sites M6 and M7. (Part B). Exposed indurated surface of late-Pleistocene dune ridge (large arrow) in foreground and remobilized Holocene dune cover (small arrow) in background (above dashed line) from a location between sites G5 and G6 in the Guerrero Negro dune sheet (Fig. 4). The morphology of the late-Pleistocene dune ridge is preserved from recent (Holocene) eolian reactivation processes by the armoring of an indurated late-Pleistocene Bw horizon (reddish-brown in color). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

should be performed to reach and date these deposits to fully constrain the origins of the Magdalena and Guerrero Negro dune sheets. In this article, a Holocene transgressive mechanism is proposed to explain the origins of the Holocene barrier islands and lagoons in the Magdalena and Guerrero Negro study areas. Mechanical drilling and dating of the basal barrier and lagoon deposits are needed to verify and constrain the proposed mid-Holocene marine transgressive mechanisms.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeolia.2017.07.003.

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